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RNG turbulence models have been incorporated into a Spectral Element Code to calculate compressible turbulence.

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Final Progress Report on AFOSR Project:

DEVELOPMENT AND VALIDATION OF RNG METHODOLOGY FOR COMPRESSIBLE TURBULENCE

(AFOSR Grant 90-0261)

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All three different categories of tasks described in our AFOSR proposal (Grant 90-0261) were completed succesfully: (a) Development of Renormalization Group theory (RNG) for compressible turbulence; (b) Design and Measurements of a compressible boundary layer experiment, and (c) Development of spectral element algorithms for compressible flows. A brief summary follows:

THEORY: RNG methodology for compressible turbulence

On the theoretical side first, the new results obtained for compressible turbulence are: (1) At the large scales the effective sound velocity in compressible turbulence is scale-dependent and obeys a universal equation of state. (2) The effective, scale-dependent Mach number based on the *rms* value of velocity approaches a fixed point corresponding to effectively subsonic flow. (3) The potential component of the velocity field (sound waves) does not alter the scaling of the energy spectrum of incompressible (rotational) component. This *decoupling of events* in rotational and compressibility effects suggests that most of the RNG modeling for incompressible flows is also valid for compressible flows as long as compressibility is taken into account. Details of these developments can be found in papers by Yakhot and Staroselsky, while examples of RNG modeling of a massively separated flow are given in a paper by Karniadakis, Orszag and Yakhot presented by Prof. Karniadakis during an invited lecture in the Workshop on large eddy simulations (LES) of turbulent flows (December 1990, St. Petersburg, Florida, Proc. on Large Eddy Simulation for Compex Engineering Flows, Cambridge University Press, 1993).

EXPERIMENT: Multiple distortion of a supersonic boundary layer

The prototype experiment is the flow of a high Reynolds number (Mach number 2.9) turbulent boundary layer over a ramp, designed such that the boundary layer turbulence is subjected successively to longitudinal concave curvature/compression and convex curvature expansion. The overall pressure rise and change in flow direction is zero, and the differences between the incoming and outgoing boundary layer are represented solely by the nonlinear terms in the governing equations. For the particular flows studied here, two models were used: Model A, where a 20 degrees compression corner is followed by a 20 degrees centered expansion; and Model B, where the sharp corner and centered expansion surfaces are replaced by smoothly curved walls, each with a radius of curvature equal to 12 times the boundary layer thickness (δ). The distance between the two corners is about 4δ.

Earlier work by Smith and Smits has focused on the response of a Mach 2.9 boundary layer to a strong favorable pressure gradient generated by a 20 degrees expansion corner. The streamwise turbulence intensity was reduced by a factor of six, and it was found that this reduction could be accurately predicted using Rapid Distortion theory. In the present study, the combined effect of compression/expansion was examined. Downstream of the expansion corner, the boundary layer relaxes

in a region approximately 12δ long, where δ is the initial boundary layer thickness. Dramatic changes in the velocity profiles occur as a result of these successive distortions; in particular, while the velocity profile lacks a logarithmic region immediately downstream of the expansion corner, the mean flow recovers quickly and a log region soon appears. In the outer part of the boundary layer, however, the effect of the distortions is more severe and there is little sign of recovery even at the furthest downstream location. Regarding the wall shear stress, it decreases throughout the relaxation region, but by the last measurement location it has yet to reach the initial undisturbed value. Measurements of turbulence quantities have also been completed.

In summary, our results suggest that a strong residual distortion of the turbulent boundary layer exists downstream of the expansion, where the flow has turned back to its original direction. Downstream, the relaxation process is fast, and the turbulence results suggest the possibility of an overshoot, as seen in other work at subsonic speeds following longitudinal curvature. This work was supervised by Professor Smits and it was performed at the facilities of the Gas Dynamics Lab. These results were presented at AIAA 30th Aerospace Sciences Meeting, Reno, Nevada, January 1992, and at the Fourth European Turbulence Conference, Delft, The Netherlands, July 1992. The Paper at the European Turbulence Conference was selected for publication in expanded form for the bound proceedings published by Elsevier, 1993. Further publications are in preparation for Experiments in Fluids, Journal of Fluid Mechanics, Physics of Fluids A and the 25th AIAA Fluid Dynamics Conference, Boulder CO,20-23 June 1994.

ALGORITHMS: Hybrid spectral element methods for the compressible Navier-Stokes equations in complex geometries

On the numerical side, we have developed two new hybrid algorithms based on spectral element discretizations. The first method is based on non-oscillatory approximations and is capable of resolving with high accuracy a very wide spectrum of scales in the presence of shock waves. The second method is based on Flux Corrected Transport (FCT) ideas and is more robust. Both one-dimensional and two-dimensional implementations have been completed.

The underlying discretization procedure is based on a *conservative* spectral element formulation that employs cell averaging and reconstruction procedures on a *staggered* grid of Gauss-Chebyshev and Gauss-Lobatto-Chebyshev points. In addition, high-order time-differencing schemes, flux limiters, and a general spectral filter are employed to improve the quality of the solution. A major achievement is the development of inter-elemental (interfacial) boundary conditions that allow robust coupling between elements. These boundary conditions use the numerical fluxes directly and a standard characteristic decomposition algorithm. The key idea in obtaining non-oscillatory solutions with the first method is to augment the spectral space with a saw-tooth function and approximate the discontinuity *location* with *second-order* accuracy and discontinuity *magnitude* with a *first-order* accuracy. This theoretical result, first proved by Gottlieb and his group, gives great flexibility in implementation as described in our recent work . The key idea in the spectral element-FCT method is to use the spectral scheme in the antidiffusive stage in order to obtain very sharp profiles in discontinuous solutions of hyperbolic problems. Details of this work are included in the cited publications.

We have demonstrated through various models of linear advection and examples of shock formation in scalar as well as in hyperbolic systems of equations that both algorithms lead to stable, non-oscillatory solutions of high accuracy. Typically, spectral or spectral element methods perform very poorly in the presence of even weak discontinuities although they produce only exponentially small errors for smooth solutions. The developed spectral element/non-oscillatory and spectral element/FCT methods can provide spectral properties (i.e. minimum dispersion and diffusion errors) as well as great flexibility in the

discretization as a variable number of macro-elements or collocations per element can be employed to accomodate both accuracy and geometric requirements.

The production code developed during this project is based on spectral element and flux corrected transport (FCT) concepts and is appropriate for simulations of subsonic, transonic and supersonic flows. This spectral element-FCT code employs a conservative formulation that is based on one- and two-dimensional cell-averaging and reconstruction procedures, which are defined on a stagerred mesh of Gauss-Chebyshev and Gauss-Lobatto-Chebyshev collocation points. Particular emphasis is based on the construction of robust boundary and intefacial conditions in multi-dimensions. In addition, a new formulation was developed to treat the viscous terms of the compressible Navier-Stokes equations in the presence of shocks. Model problems include boundary layer flows, separated flows over expansions and compession ramps, and supersonic unsteady compressible wakes.

This part of our work was directed by Professor Karniadakis with the asistance of Dr. D. Sidilkover (Post-Doctoral Fellow in Mechanical and Aerospace Engineering) and J. Giannakouros (a Ph.D. graduate student). The collaboration with Professor D. Gottlieb has been extremely valuable; our group had meetings with his group either at Princeton or Brown University every two months.

Publications

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[2] J. Giannakouros, "A spectral element-FCT method for the compressible Navier-Stokes equations in complex geometries", Ph.D. Thesis, Dept. Mechanical and Aerospace Engineering, Princeton University, January 1994.

[3] D.R. Smith and A.J. Smits, "The effects of multiple distortions on the boundary layer in a supersonic flow," AIAA Paper #92)0309, AIAA 30th Aerospace Sciences Meeting, Reno, Nevada, January 1992.

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